Tillage-Induced Gas Fluxes: Comparison of Meteorological and Large Chamber Techniques

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Abstract: CO_2 fluxes from soils following tillage are usually large and decline rapidly with time. Establishing the time-course of the CO_2 flux in the early stages of the emission is important, but conventional micrometeorological techniques require large treated areas that take time to create. Hence chambers are often used to measure the flux. 'Chamber effects' may occur due to soil variability, chamber size and placement, and the level of turbulence in the chamber. We have compared chamber measurements of soil CO_2 flux after tillage with those calculated simultaneously by novel, non-disturbing, micrometeorological techniques suitable for small treated areas. The experimental area was a wheat field with some crop residue; 12 or 16 furrows were ploughed cross-wind in a strip 50m long and 5.6 or 7.3m wide. The chamber was a large (3.25 m^3), tractor-mounted, dynamic, closed chamber employing rapid mixing for fast response. Increases in both CO_2 and water vapour concentrations were measured with a Licor 6262 infrared gas analyser. Flux measurements required only 1 min. Three meteorological techniques were employed: one using a line–source solution, one using a solution for a semi-infinite strip, and one using a backward Lagrangian stochastic (bLs) model. Inputs were measurements of wind speed and gas concentrations on upwind and downwind edges of the treated area at 0.2m above the surface. Chamber and micrometeorological measurements were made for 1h before and 2h after ploughing. There was good quantitative agreement between all 3 micrometeorological methods for both CO_2 and water vapour fluxes, but the agreement between them and the chamber was variable, depending on wind speed. All methods agreed at a wind speed (at 0.25m) of 2.27 m s^{-1}, but the chambers gave higher fluxes when the wind speed was less than that value and higher fluxes above it. Interestingly, the 'wind' speed within the chamber is a constant 2.2 m s^{-1}. The clear inference is that wind speed has a large effect on gas fluxes from the tilled soil, particularly in the early stages of the emission. It is suggested that the micrometeorological techniques employed in this study provide attractive alternatives to chambers or could be used to calibrate 'chamber effects'.

INTRODUCTION

Quantifying the effects of tillage operations on carbon sequestration by agricultural soils requires unequivocal measurements of CO_2 exchange between soil and atmosphere. Micrometeorological methods are often preferred for this task because they do not disturb the microclimate and do not influence the exchange process. However, emissions of CO_2 following tillage are highly transient, reducing from high initial emissions to low levels within a matter of minutes (Reicosky and Lindstrom, 1993; Reicosky, 2003). Establishing the time-course of the emission in its early stages is thus paramount, but conventional micrometeorological approaches require large treated areas for their application, which will usually require impossibly long times to create. Chambers are often used as an alternative, but the effects of enclosure on the emission, so-called 'chamber effects', can be large and must be evaluated. Reicosky (2003) indicates that differences in wind speed and turbulence between the chamber and the unenclosed environments are particularly important in evaluating the effects of tillage on CO2 loss. We report here the use of novel micrometeorological methods suitable for small treated areas to 'calibrate' chamber measurements of CO_2 emissions following tillage episodes.

METHODOLOGY

Emissions of CO_2 and water vapour from a newly tilled field were measured simultaneously with a large, portable, dynamic chamber and 3 different micrometeorological techniques.

Site

The work was carried out on a fallow wheat field with some crop residues, located at the USDA-ARS Research Farm at Swan Lake, MN. Initial measurements of emissions from the untilled soil were made for approximately 1h. Then 3 or sometimes 4 rapid passes were made in succession with a 4-bottom mouldboard plough to create a tilled strip 50m long and 5.5 or 7.3m wide, tilled to a depth of 0.25m. The strip encompassed 12 or 16 furrows. Measurements of gas emissions commenced as soon as the last pass was completed and continued for 2 to 3h.

Chamber

The chamber was a large, tractor-mounted, dynamic, closed chamber, employing rapid mixing for fast equilibration and has been described by Reicosky and Lindstrom (1993). The surface area enclosed was 2.71m^2 and the volume of the head-space 3.25m^3. 'Wind speed' in the chamber at a height of 0.2m above the ground was 2.2 m s^{-1}. CO_2 and water vapour concentrations in the chamber were measured with a LI-COR 6262 infrared gas analyser at 1s intervals during a total enclosure time of only 1 min. Flux calculations were made from observations over the last 30s of enclosure. Measurements were made repeatedly at the same location about every 2 min during the experiment. Fifteen such experiments are examined here. The influences of pressure and wind speed on CO_2 and water vapour losses in chambers of this type are reported in a companion paper at this meeting by Reicosky (2003).

Micrometeorological Methods

Three techniques were employed: one using mathematical solutions for emissions from line-sources, another using solutions for emissions from a semi-infinite strip, and a third based on a Lagrangian description of atmospheric dispersion. Inputs were measurements of gas concentrations at 0.2m above the ground on upwind and downwind edges of the tilled strip and measurements of horizontal wind speed at the same height.

Line source solutions

These are due to a model of atmospheric dispersion from semi-infinite, cross-wind line sources developed originally by Sutton (1953) and used more recently by Denmead *et al.* (1982) to characterise emissions of NH_3 following injection of anhydrous NH_3 fertiliser into a fallow cotton field. In the present application, the model was used to calculate the contribution c_i of each ploughed furrow (an equivalent line source) to the total enrichment of CO_2 and water vapour concentrations C at a given height and distance downwind. The model uses power-law profiles of wind speed u and eddy diffusivity K:

$$u = u_1 (z/z_1)^m ,$$

and

$$K = K_1 (z/z_1)^n ,$$

where u_1 and K_1 are the values of u and K at a reference height z_1, and m and n are constants whose values depend on surface roughness and atmospheric stability. Assuming conjugate power-laws so that $n = 1 - m$,

$$c_i(x_i, z) = \frac{Q}{u_1 \Gamma(s)} \left\{ \frac{u_1}{(2m+1)^2 K_1 x_i} \right\}^s \exp\left\{ -\frac{u_1 z^{2m+1}}{(2m+1)^2 K_1 x_i} \right\},$$

where x_i is the distance of furrow i downwind from the point at which C is measured, z is the height of measurement, Q is the source strength, $s = (m + 1) / (2m + 1)$, and Γ denotes the incomplete gamma function. Finally, Q is calculated by noting that $C = \Sigma c_i$, and the mean flux per unit area in the treated zone F is given by $F = Q/w$, w being the width between furrows.

In our experiments, concentrations of CO_2 and water vapour were measured at 0.2m above the undisturbed soil surface on upwind and downwind edges of the tilled strip employing LI-COR 6262 infrared gas analysers and a fast-response hot-wire anemometer. Wind speeds were measured at the same height with a hotwire anemometer. Wind direction was also recorded in order to calculate the x_i. The value of the power-law coefficient m was set at 0.225, following observations of wind speed profiles over a similar tilled surface by Denmead *et al.* (1982). Data were collected at a frequency of 2Hz and were later processed into 1-min averages. The emission was modelled by calculating steady-state solutions for successive 1-min periods.

Solutions for a semi-infinite strip

Developed by Philip (1959), these relate downwind concentrations to the mean surface flux within the strip. They use the same power law profiles and have much the same mathematical form as Sutton (1953), but allow for different boundary conditions at the soil surface: constant concentration or constant flux or a mix of both. The solutions for constant concentration allow for the effects of wind speed itself on the emission rate and appear more appropriate for the present application. Details of the calculations can be found in Philip (1959). Fluxes were calculated from the same data set as used in the line source analyses and again, the emission was modelled by a series of 1-min steady-state solutions for successive 1-min periods.

Backward Lagrangian Dispersion Analysis

The analysis is described by Flesch *et al.* (1995). It uses computer-simulated releases to track the trajectories of air parcels backward in time form the point of concentration measurement to the source. It calculates the flux F from the number of touchdowns in the source area. Required input information is surface roughness, the geometry of the source and the location of the sensor relative to it, the mean wind speed $\overline{u}$ and gas concentration in excess of background $\overline{C}$ at the measuring point which is at height z, and atmospheric stability. Solutions have the form

$$F = \alpha \overline{u_z}\,\overline{C_z}$$

where α is a coefficient calculated by the analysis for the particular situation. In the present application, fluxes were calculated for successive 1-min periods from the same data set used in the other micrometeorological analyses.

RESULTS AND DISCUSSION

Figure 1 illustrates the general character of the emission measurements and indicates that spatial heterogeneity was unlikely to have influenced the comparison of methods. It shows simultaneous time courses of the enrichment in CO_2 at 0.2m above the ground on the downwind edge of a 7.3m tilled strip, measured across 2 transects, 3m apart. CO_2 was evolved immediately on tilling and the emission decreased rapidly thereafter. Typically, the initial enrichment was tens of ppm, decreasing to <10 ppm, but not to zero, after 2 or 3h. The excellent agreement between the 2 transects suggests that emissions were uniform within the tilled area.

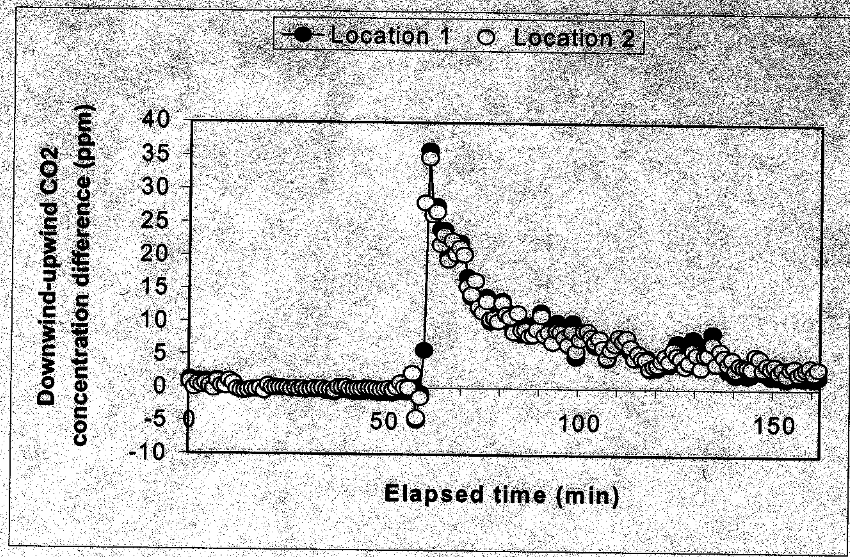

Figure 1. Simultaneous time-courses of differences in 0.2m CO_2 concentration between downwind and upwind edges of a tilled strip for 2 transects, 3m apart. The strip was 7.3m wide. Measurements cover periods before and after tilling.

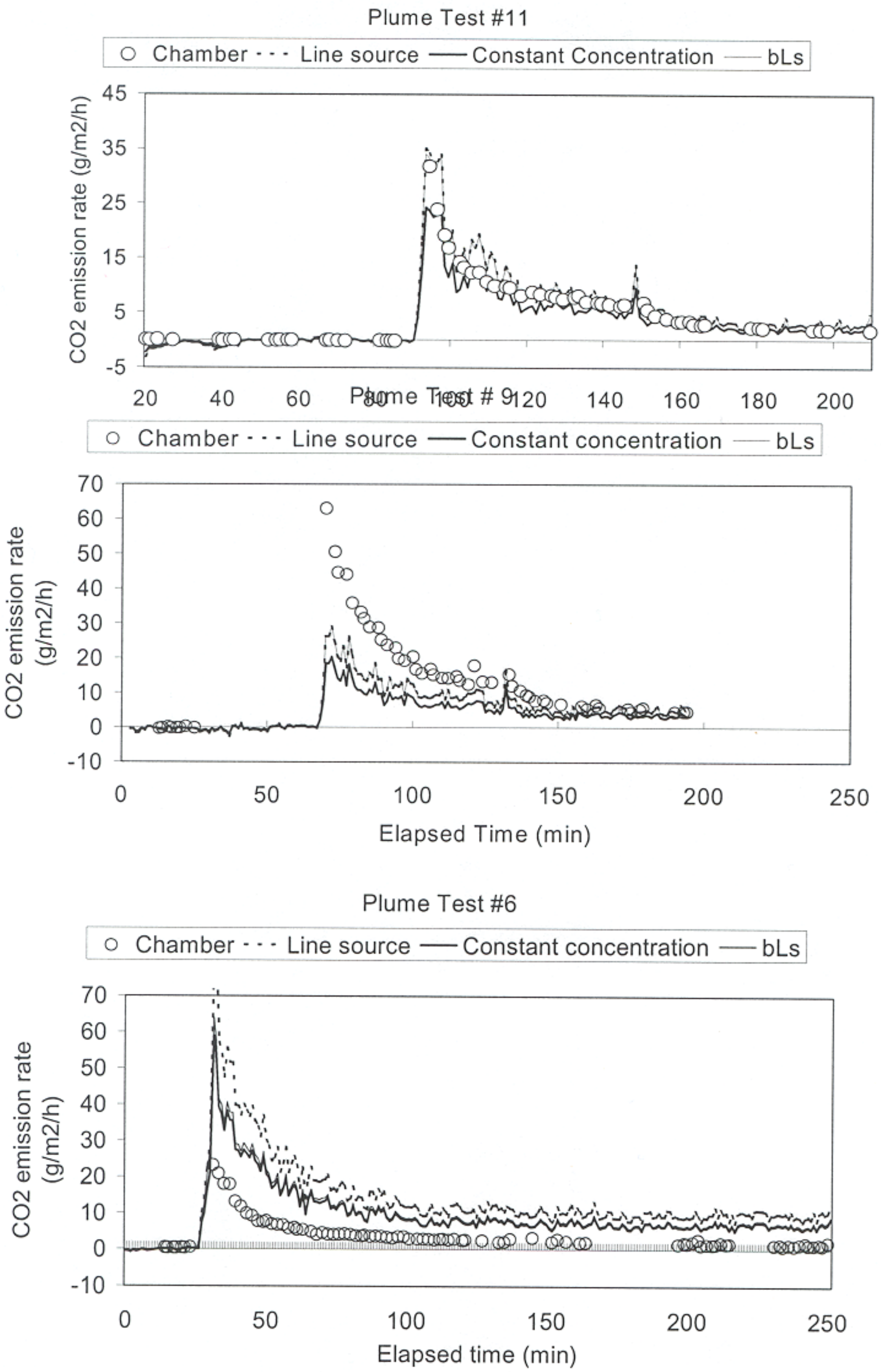

Figure 2. Chamber and micrometeorological CO_2 emission rates in three experiments.

Figure 2 shows chamber and micrometeorological CO_2 fluxes in 3 representative experiments. The micrometeorological fluxes exhibited the same time-trends as the chamber fluxes: large emissions immediately after tillage decreasing rapidly with time. However, there were often quite large quantitative differences between the two approaches. In the first experiment represented in Figure2, Plume Test #11, the fluxes agreed very well, but in the second (Plume Test #6), chamber fluxes were very much less than the micrometeorological ones and in the third (Plume Test #9), they were very much more. Overall, the micrometeorological fluxes agree well with each other, although the line source analysis predicted fluxes that were some 20% higher than the other 2 approaches. There was little to choose between the bLs and constant concentration estimates, which agreed to within 10%. The same remarks were true for the water vapour fluxes.

The main difference between the 3 experiments represented in Figure2 was the wind speed outside the chamber. In the first experiment, $\overline{u_{0.2}}$ was 3.7 m s^{-1}, in the second, it was 0.97 m s^{-1} and in the third, 2.05 m s^{-1}. The effect of wind speed is explored further in Figure3 which shows the ratios of micrometeorological fluxes of both CO_2 and water vapour, calculated for constant concentration boundary conditions, to chamber fluxes for all the available data, as a function of wind speed measured at 0.2m. The trend line in the figure shows that the ratio increased with external wind speed, from values <<1 for a wind speed of 1 m s^{-1} to values >2 for winds in excess of 3 m s^{-1}. The dashed lines indicate a ratio of 1 for a wind speed of 2.27 m s^{-1} which is virtually identical with the chamber 'wind speed' of 2.2 m s^{-1}. Very similar results were obtained for the line source and bLs analyses, the former giving a ratio of 1 at an external wind speed of 1.82 m s^{-1} and the latter at a wind speed of 2.13 m s^{-1}. The clear inference is that wind speed (or turbulence) has a large effect on gas emissions from newly tilled soil. In the unenclosed condition, this results in the dependence of flux on wind speed evident in Figure 3, but of course, the same influence is not evident in the constant wind conditions of the chamber. It is probable that higher winds (or turbulence) enhance both the transport of gases to the soil surface and their removal from the surface by convection.

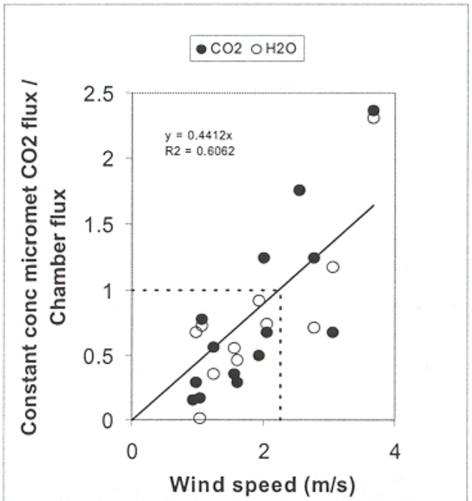

Figure 3. Effect of wind speed measured at 0.2m height on ratio of 'constant concentration' micrometeorological fluxes of CO_2 and water vapour to respective chamber fluxes. Dashed lines indicate the wind speed at which the best fit ratio is 1, viz., 2.27m s^{-1}.

CONCLUDING REMARKS

The wind speed dependence confirms the results of Reicosky (2003), who employed a quite different experimental approach to study this effect, based on varying pressures and wind speeds inside the chamber. It also reinforces his warning that caution should be used when interpreting and extrapolating chamber-measured fluxes.

The good agreement between the three micrometeorological flux estimates, particularly the agreement between the line source and constant concentration methods and the bLs method, which has an altogether different theoretical basis, suggests that they are all acceptable approaches. Further, they are relatively simple to employ. They are thus attractive alternatives to chambers for gas flux measurement in these small plot situations. They could also be used, as here, to calibrate 'chamber effects'. Another possible approach is to match wind speeds in the chamber to those outside it, as has been done in some chambers used for measuring ammonia emissions, e.g. Lockyer (1984), although the engineering becomes more complicated.

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